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DRIVE TURBINE SYSTEMS FOR 20-INCH TURBOFAN SIMULATORS
II. CORE TURBINE DESIGN

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SUMMARY

A study has been made to evolve drive-turbines for a given set of 20-inch turbo-fan simulators. The simulators had both single-stage and two-stage fans that had design pressure ratios as low as 1.25 and as high as 3.0. The desired objective of the study was to be able to drive all of the single-stage fans with one core turbine and to drive all of the two-stage fans with this same core turbine in combination with a duct turbine.

This report describes the core turbine. Included herein are the design operating conditions, design velocity diagram and a power-speed envelope determined by an off-design performance procedure. Also discussed herein is the adaption and scaling of an existing turbine design to this particular application.

INTRODUCTION

A number of research projects on turbofan simulators are currently in progress at the NASA Lewis Research Center. The simulators considered herein have fans of 20-inch tip diameter. The fans are both single-stage and two-stage configurations and the aggregate of their operating conditions covers a wide range of pressure ratio, speed and power require-

ment. The turbine systems drive the fans by being directly coupled to the fan shaft. A source of high pressure air at moderate temperature is available for the drive turbines at the test site. The general purpose of this study is to evolve the turbine drive systems to power these fans.

An optimum turbine drive system, as mentioned in reference 1, would be one in which one core turbine would drive all of the single-stage fans, and, when teamed with one duct turbine design, would drive all of the two-stage fans. This system would require the minimum number of turbine designs to be conducted. In order to pursue this plan it was first necessary to evolve a duct turbine design and to determine its performance for the various two-stage fan operating conditions. The make up power requirement of the core turbine can then be ascertained for the two-stage fan operating conditions.

The design of the duct turbine is described in reference 1. Adjustable stators were found to be necessary for the off-design operation in the reference. The use of adjustable stators enabled the duct turbine to accommodate the fan mass flow at all operating points and caused the duct turbine power output to increase as the total power requirement increased. This in turn resulted in a core turbine maximum power requirement that was fairly constant over the range of speed and not significantly greater than the highest powered single-stage fan. The core turbine, however, does have the problem of producing this level of power over a wide range of speed.

This report describes the design of the core turbine. Included herein is a performance map for the core turbine determined by an analytical procedure. This map will then be used to ascertain the capability of the

core turbine to develop the required power at all of the operating conditions.

SYMBOLS

i	incidence angle, deg
Δh	specific work output/Bru/lb
N	rotative speed, rpm
p	absolute pressure, atmospheres
U	blade velocity, ft/sec
V	absolute gas velocity, ft/sec
W	gas velocity relative to moving blade row, ft/sec
w	mass flow rate lb/sec
α	absolute gas flow angle, measured from axial direction, deg
β	gas flow angle, relative to moving blade row, measured from axial direction, deg.
δ	ratio of inlet pressure to U.S. standard sea-level pressure
φ	blade orientation or stagger angle, deg.
η	efficiency
θ_{cr}	squared ratio of critical velocity at turbine inlet to critical velocity of U.S. standard sea-level air

Subscripts

cr	conditions at Mach 1
m	mean radius
u	tangential component
0	station at fan inlet see figure 3
1	station at fan outlet
2	station at duct turbine inlet
3	station at duct turbine stator outlet
4	station at duct turbine outlet
5	station at core turbine inlet
6	station at core turbine 4th stage stator outlet
7	station at core turbine outlet

Superscripts

'	total state

POWER REQUIREMENTS AND CONCEPTUAL LAYOUTS

The fan power-speed envelope that specifies the turbine drive system requirements is shown in figure 1. The single-stage fans have pressure ratios of 1.5 or lower while the two-stage fans have pressure ratios from 2.0 to 3.0. As mentioned in reference 1 the lowest power requirement of the two-stage fans is nearly twice the highest power requirement of the single-stage fans. In addition to the power requirement level, the expansion energy available at the fan outlet is considerably greater for the two-stage fans. The expansion energy recoverable by the duct turbine is shown in figure 2 as a fraction of the total power requirement. The fraction of power available from the duct turbine is seen to be substantial at pressure ratios of 2.0 or greater. This fraction decreases rapidly as the pressure ratio is decreased below 2, being .29 at a fan pressure ratio of 1.5 and actually negative at a pressure ratio of 1.25. It was therefore considered feasible, as discussed in reference 1, to provide all the driving power for the single-stage fans with the core turbine and to drive the two-stage fans with both the core turbine and the duct turbine. These power drive systems are shown conceptually in figure 3. The duct turbine was assumed to be limited to a maximum tip diameter of 20 inches (fan tip diameter) and to a minimum hub diameter of 10 inches. This minimum hub diameter was specified in order to contain the core turbine and its supply plenum within the center body of the simulator.

The complete power-speed requirement envelope for the core turbine is shown in figure 4. For tip speeds of 1160 ft/sec and lower, the power requirements are those of the single-stage fans. The power require-

ment for tip speeds in excess of 1160 ft/sec is the amount of two-stage fan power that is not supplied by the duct turbine. The maximum power required of the core turbine varies from 1300 horsepower for the pressure ratio of 2.0 fan to 2030 horsepower for the pressure ratio of 3.0 fan. It can be noted in figure 4 that the core turbine is required to produce this general level of power over a wide speed range from a fan tip speed of 910 ft/sec to 1780 ft/sec.

CORE TURBINE DESIGN

This section consists of the velocity diagram study and turbine blading design.

Velocity Diagrams

The limits and state of the air supply available to operate the core turbine were specified as follows.

Maximum mass flow rate	25 lbs/sec
Turbine inlet pressure	300 lbs/sq. in. absolute
Turbine inlet temperature	200°F

The selection of the core turbine design point was based on the core turbine delivering the maximum power at the low speed range with a 10 percent reserve of inlet pressure. Accordingly the design conditions for the core turbine were:

Mass flow rate	21.8 lb/sec
Power	2080 horsepower
Fan tip speed	1035 ft/sec
Turbine inlet pressure	270 lbs/sq. in. absolute

A four-stage turbine with an 8.075 inch mean diameter was found to meet these requirements with a stage loading factor $(\Delta V_u/U)_m$ of 2.42. A stage efficiency of .89 was estimated for this design using reference 2 for an axial-velocity-to-blade-speed ratio, $(V_x/U)_{m_1}$ of .82. The type of velocity diagram used was symmetrical with respect to

whirl velocities, that is; $V_{u6m} = W_{u7m}$ and $W_{u6m} = V_{u7m}$. The axial velocity was made to increase 10 percent through the rotors and to decrease 10 percent through the stators so as to increase the reaction across the rotor hub section. A free vortex whirl distribution was used with constant axial velocity at all the freestream stations. The velocity diagram of the fourth stage is shown in figure 5. The mean radius was constant, and the mean section velocity diagram was the same for all four stages, however the critical velocity ratios increase slightly in the aft stages because of the temperature drop from inlet to outlet. The diagram does not indicate any unusually severe problems such as high flow Mach number or excessive blade turning angle. The diagrams for the forward stages would have lower Mach number as mentioned previously, and their hub and tip diagrams would be more similar to the mean because of the decreasing blade height. The hub-tip radius ratio varied from .899 at the inlet to .621 at the outlet. The flow path projection is shown in figure 6.

Blade Section Layout

It was noted previously that the velocity diagram indicated this to be a conventional design. It was therefore considered feasibly (and economical) to adapt an existing blading design to this application if possible. The turbine of reference 3 appeared to be the most likely candidate. The reference turbine had symmetrical velocity diagrams and a stage loading factor of 3.1 based on the design point conditions. Thus only minor adjustments were required to adapt the blading of reference 3 to the mean radius velocity diagram of this application. These angle adjustments and the resulting incidence angles at the mean radius are shown in Table I. It was not anticipated that any appreciable

performance losses would result from these incidence angles.

The blading of the reference turbine was of constant cross section, that is, invariant with radius. The turbine exhibited good design point performance as well as desirable off-design characteristics even though the last stage had relatively long blades (radius ratio; .665). The range of radius ratio for the four-stage core turbine (.899-.621) was not significantly different than that of the reference turbine (.800-.665). It was therefore felt that constant cross-section blading, which is also desirable from an economic standpoint, could be used for the core turbine.

It was decided from these considerations to use constant cross section blading geometry scaled from the turbine of reference 3 with the adjusted stagger angles as shown in Table I. The stator blading coordinates and geometry are shown in Table II and that for the rotor in Table III. As can be noted in Table III all four rotors have the same blading cross section. The stator blading of stages 3 and 4 also have the same cross section as may be noted in Table II. The stator of stage 2 has a similar shape, however, the number of blades and blade size were scaled differently (from stages 3 and 4) to alleviate a vibrational stress condition.

OFF DESIGN PERFORMANCE

As previously noted, the core turbine is required to deliver from 1300 to 2030 horsepower over a wide range of speed. It is therefore necessary to estimate the off-design performance of the core turbine to determine its maximum power-speed characteristic. The off-design

performance was determined using the mean-radius blade angles and the method of reference 4. The resulting performance map is shown in the conventional parameters in figure 7. The constant pressure ratio lines are seen to be fairly flat, that is the equivalent specific work changes only moderately over the speed range. This characteristic would be expected for the type of a diagram used for the core turbine. Because of the low blade speed and high stage work factor, a change in blade speed has only a small effect on the air flow angles relative to the blading. This type of characteristic is also desirable because of the versatility desired in the core turbine.

The turbine off-design performance map is replotted in figure 8 as a power-speed map. The fan-drive power speed requirements are superimposed on the figure. The turbine is seen to cover most of the power-speed requirement adequately. The turbine capability is marginal only for the pressure ratio 3 fan at the highest speed. It should be recalled that the design procedure included a 10 percent reserve on turbine inlet pressure. By using this reserve another 220 horsepower can be obtained. Thus this turbine design can supply the driving power for the single stage fans and the make-up power required when operating the two-stage fans.

CONCLUDING REMARKS

By using an adjustable stator duct turbine, it appears that the two

turbines can supply the driving power for all of the simulator power-speed range specified. There is some degree of uncertainty in this observation since it is based on estimated design point turbine efficiencies and off-design performance estimation procedures. The core turbine does, however, appear to have an adequate excess power capability for driving the single-stage fans and for supplying the make-up power required for the 2.4 pressure-ratio two-stage fan, which is the two-stage fan of most immediate interest. The turbine performance obtained from those tests could then be used to ascertain if any power development problems are indicated at the high-speed high-pressure-ratio condition.

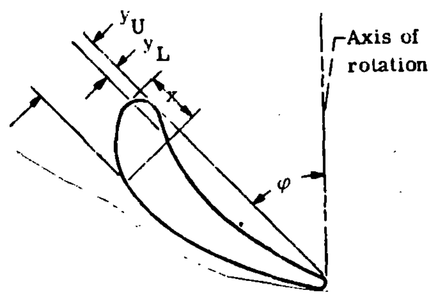
REFERENCES

1. Whitney, Warren J.: Drive Turbine Systems for 20-Inch Turbofan Simulators. 1 - Duct Turbine Design. NASA TM X-68081, 1972.
2. Horlock, John H.: Axial Flow Turbines: Fluid Mechanics and Thermodynamics. Butterworth, Inc., 1966.
3. Vanco, Michael R.: Performance Data for a Small Low-Specific-Speed Ten Stage Turbine Tested in Argon. NASA TM X-52892, 1970.
4. Flagg, E. E.: Analytical Procedure and Computer Program for Determining the Off-Design Performance of Axial-Flow Turbines. NASA CR-710, 1967.

TABLE I GEOMETRY ADJUSTMENT
REQUIRED TO ADAPT REFERENCE 3
TURBINE TO CORE TURBINE APPLICATION

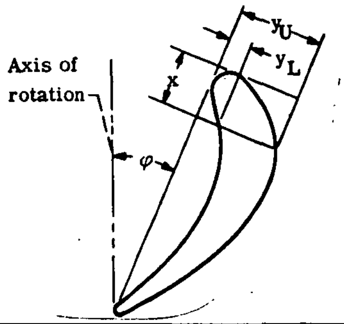
	Adjustment Angle, $\Delta\varphi$, Deg	Inlet Incidence Angle, i, Deg
1st Stage Stator	-0.79	-0.79
2nd, 3d, 4th Stage Stators	-0.79	7.4
All Rotors	-3.03	8.02

TABLE II CORE TURBINE STATOR BLADE COORDINATES



1st Stage			2nd Stage			3rd & 4th Stages		
Number of Blades								
34			31			53		
Orientation angle φ, deg								
41° 7'			30° 48'			30° 48'		
X, in.	Y_U, in.	Y_L, in.	X, in.	Y_U, in.	Y_L, in.	X, in.	Y_U, in.	Y_L, in.
.000	.038	.038	.000	.073	.073	.000	.043	.043
.040	.134	-----	.051	.218	-----	.030	.128	-----
.080	.190	.016	.103	.303	-----	.060	.177	-----
.120	.230	.034	.154	.359	.054	.090	.210	.032
.160	.256	.048	.205	.396	.103	.120	.232	.060
.200	.274	.060	.256	.418	.136	.150	.245	.080
.240	.284	.070	.308	.431	.158	.180	.252	.092
.280	.289	.078	.359	.436	.172	.210	.255	.101
.320	.290	.082	.410	.433	.182	.240	.254	.107
.360	.288	.088	.462	.427	.185	.270	.250	.108
.400	.294	.090	.513	.415	.185	.300	.243	.108
.440	.276	.091	.564	.398	.180	.330	.233	.105
.480	.266	.090	.616	.378	.174	.360	.221	.102
.520	.254	.088	.667	.355	.167	.390	.208	.098
.560	.242	.086	.718	.328	.156	.420	.192	.092
.600	.228	.083	.769	.300	.144	.450	.176	.084
.640	.212	.079	.820	.269	.128	.480	.158	.075
.680	.194	.074	.872	.233	.113	.510	.137	.066
.720	.176	.068	.923	.198	.095	.540	.116	.056
.760	.156	.061	.975	.162	.074	.570	.095	.044
.800	.136	.054	1.026	.121	.055	.600	.071	.032
.840	.114	.045	1.077	.080	.033	.630	.047	.020
.880	.092	.036	1.128	.033	.009	.660	.020	.005
.920	.070	.026	1.157	.006	.006	.677	.004	.004
.960	.046	.016	-----	-----	-----	-----	-----	-----
1.000	.021	.004	-----	-----	-----	-----	-----	-----
1.022	.005	.005	-----	-----	-----	-----	-----	-----

TABLE III CORE TURBINE ROTOR BLADE COORDINATES



All Four Stages		
Orientation Angle, φ, 29° 3'		
Number of Blades, 59		
X, in.	Y_U, in.	Y_L, in.
.000	.038	.038
.020	.099	----
.040	.138	----
.060	.166	----
.080	.188	.028
.100	.202	.048
.120	.212	.063
.140	.220	.074
.160	.226	.083
.180	.228	.090
.200	.228	.094
.220	.226	.096
.240	.224	.098
.260	.219	.098
.280	.213	.097
.300	.206	.096
.320	.198	.093
.340	.190	.090
.360	.180	.086
.380	.169	.080
.400	.158	.076
.420	.146	.070
.440	.133	.064
.460	.120	.057
.480	.106	.050
.500	.091	.042
.520	.076	.034
.540	.060	.026
.560	.044	.017
.580	.027	.008
.600	----	----
.603	.005	.005

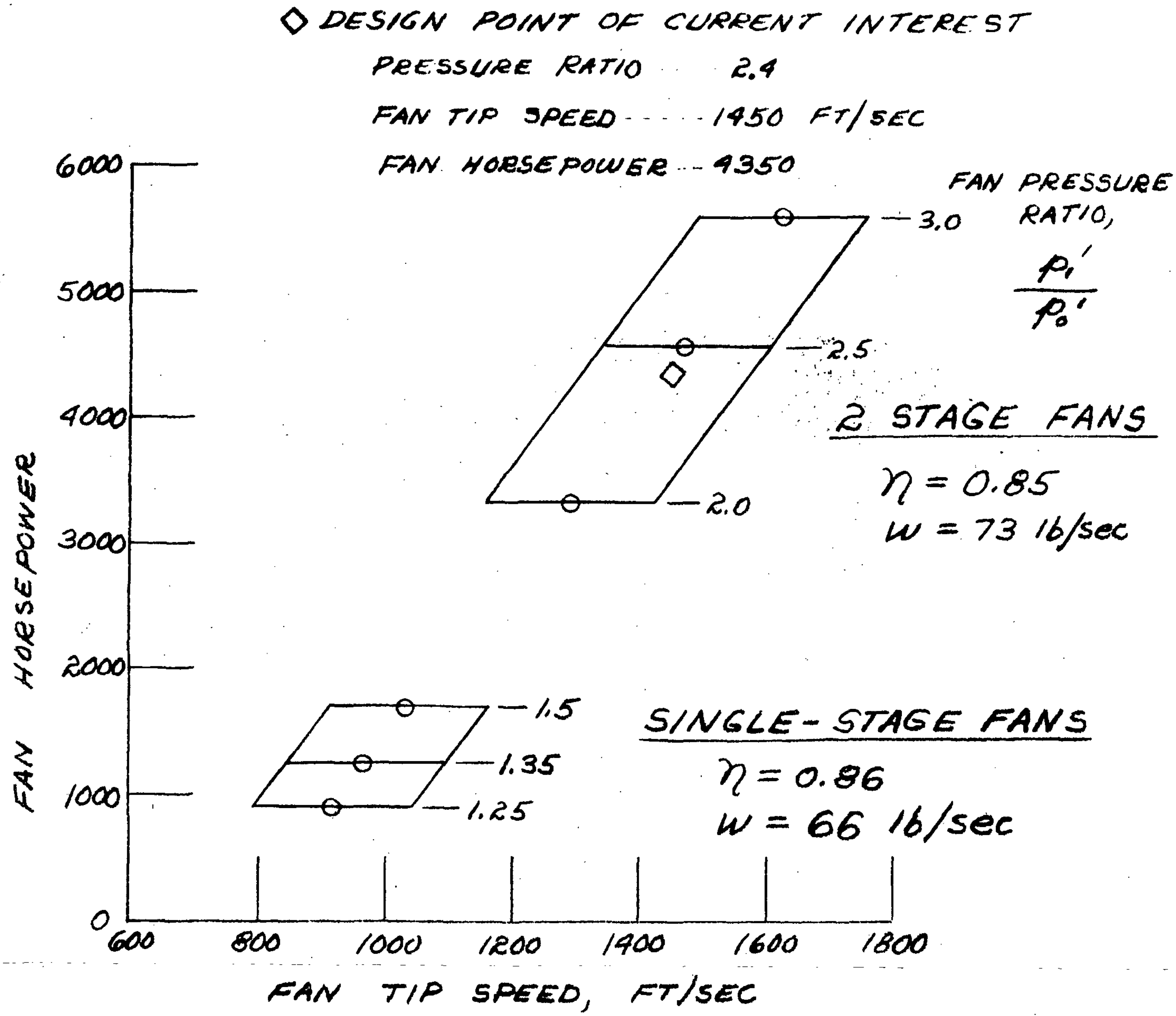


FIGURE 1.- POWER-SPEED ENVELOPES FOR SINGLE-STAGE AND 2-STAGE FANS, AMBIENT CONDITIONS — STANDARD ATMOSHERE

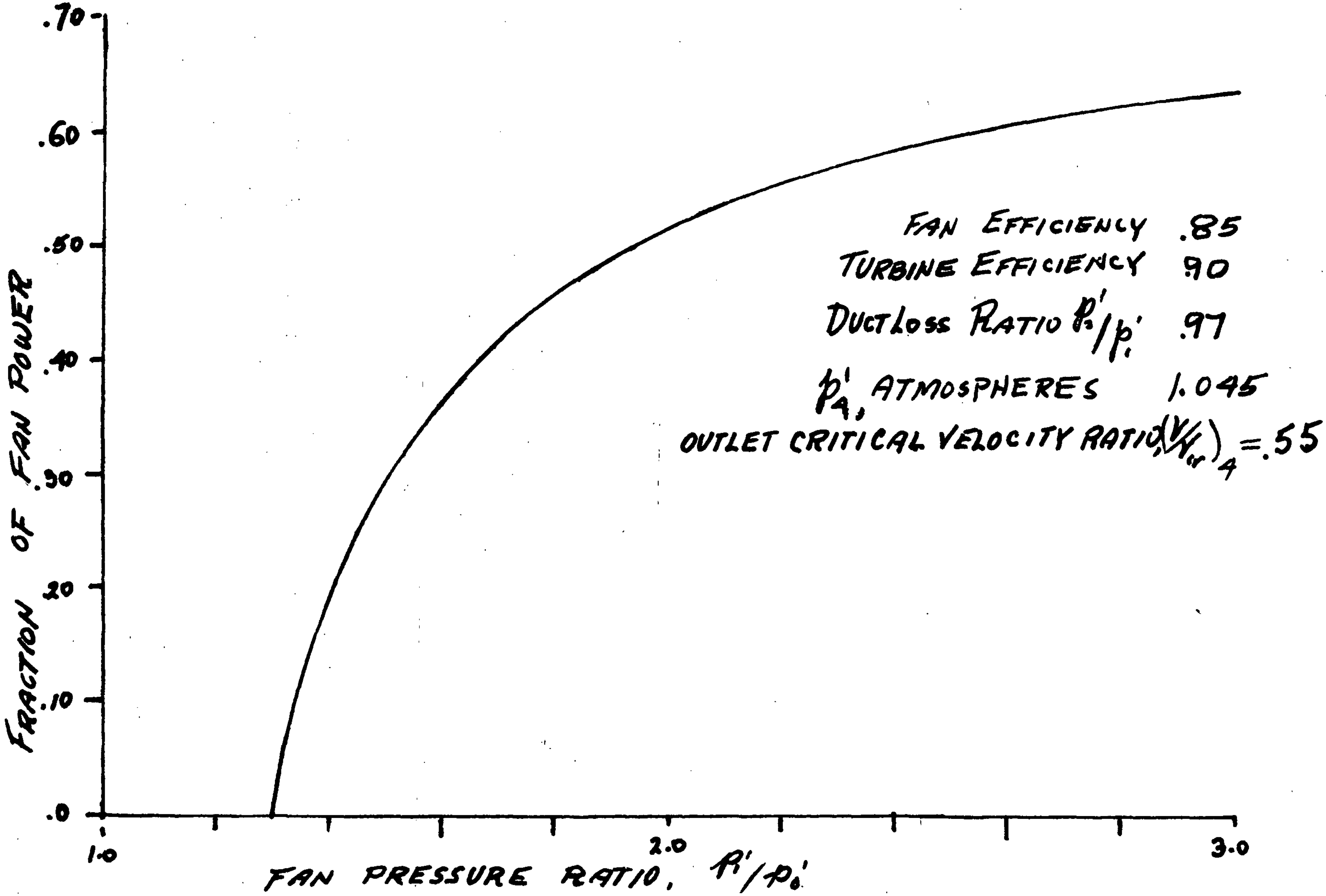
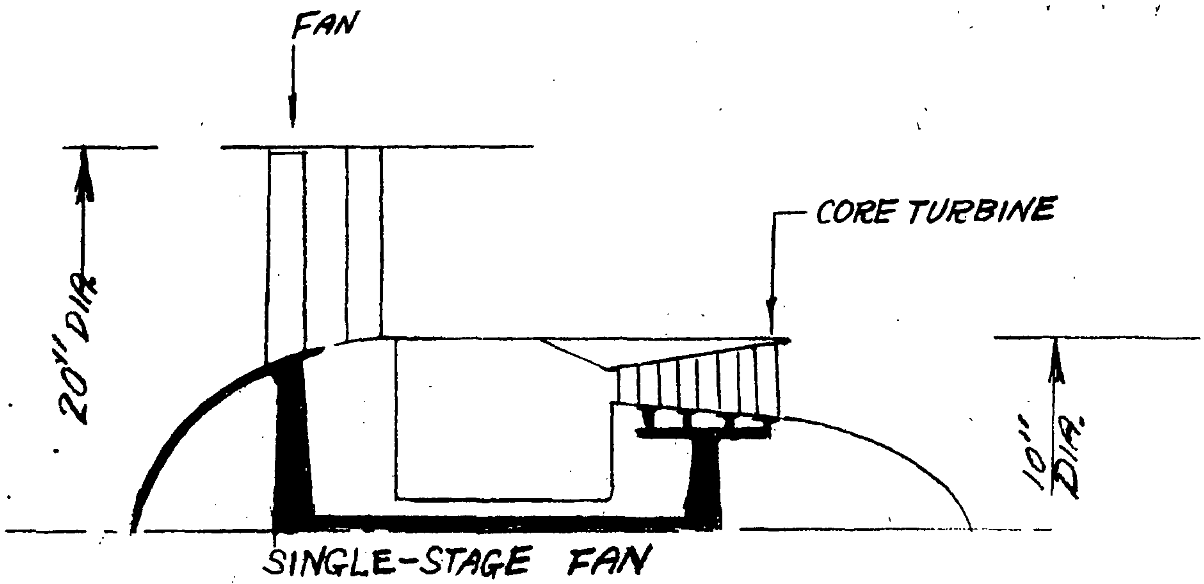


FIGURE 2 FRACTION OF FAN POWER AVAILABLE FROM DUCT TURBINE



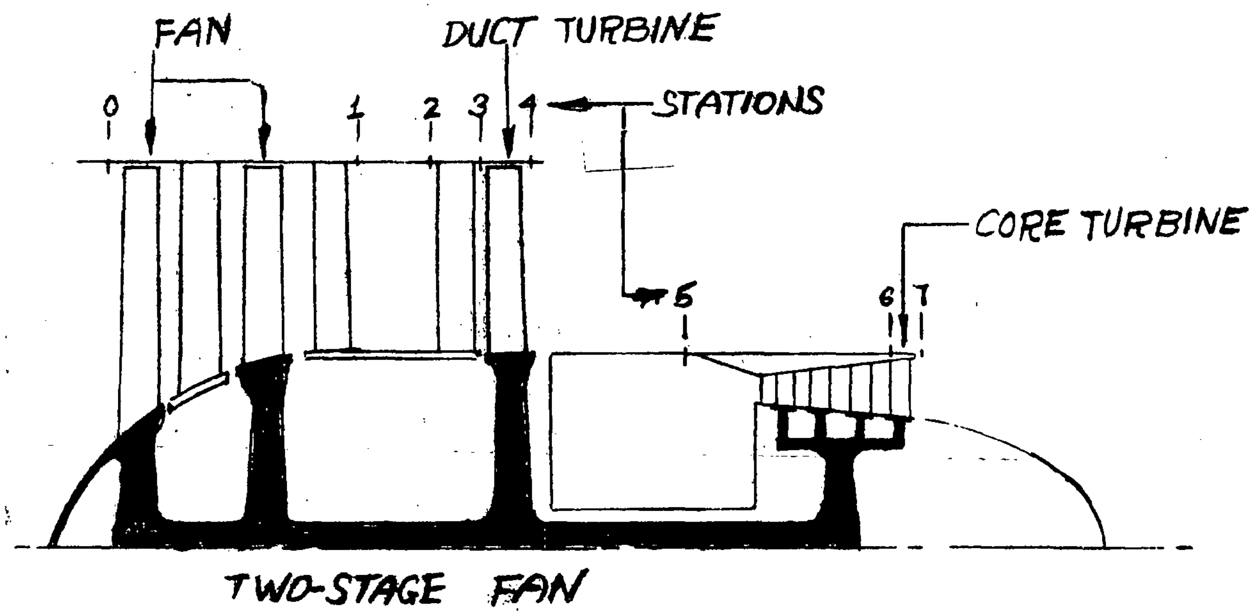


FIGURE 3 SKETCH OF TURBINE DRIVE SYSTEMS FOR 20-INCH TURBOFAN ENGINE SIMULATORS

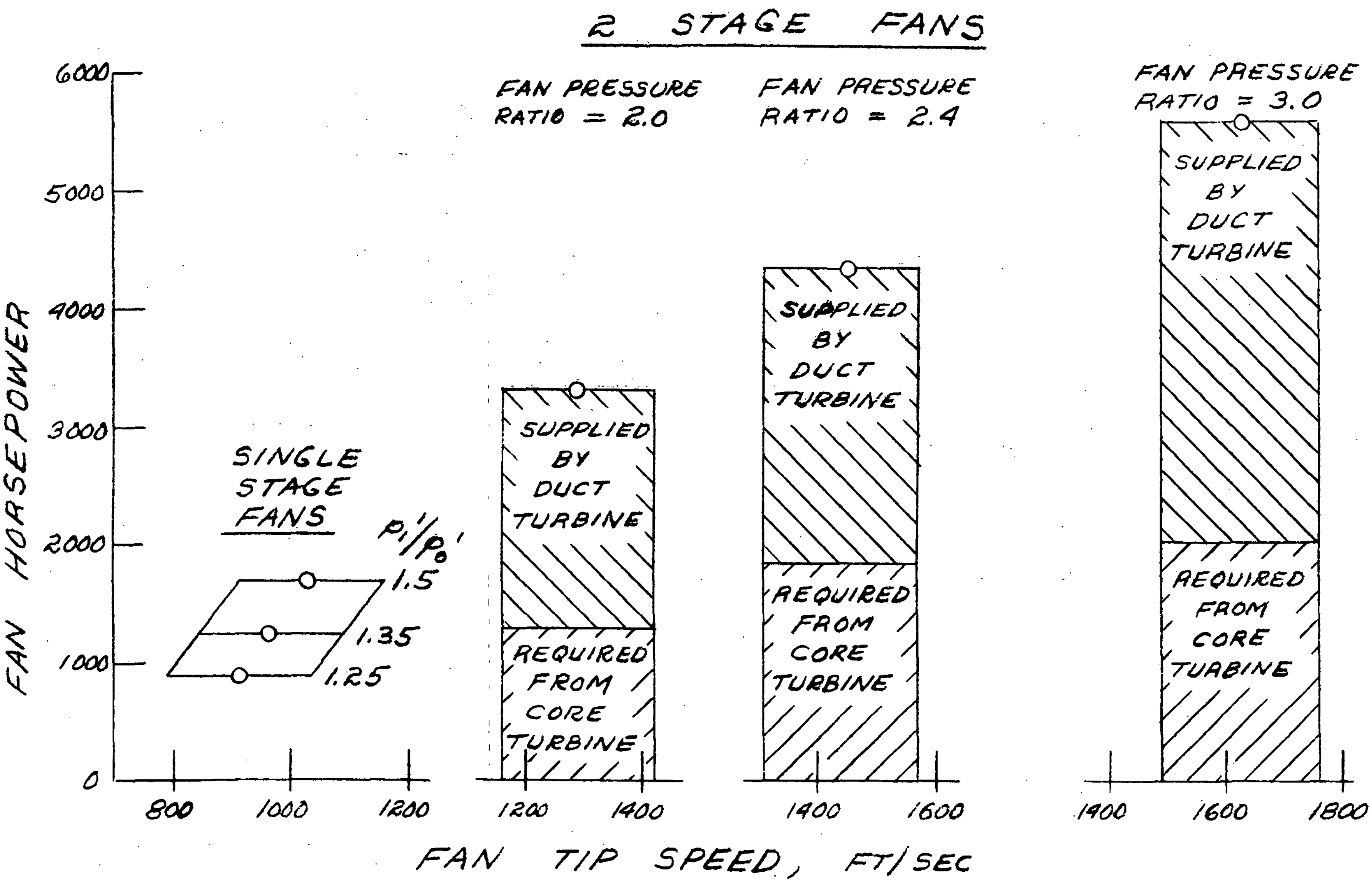
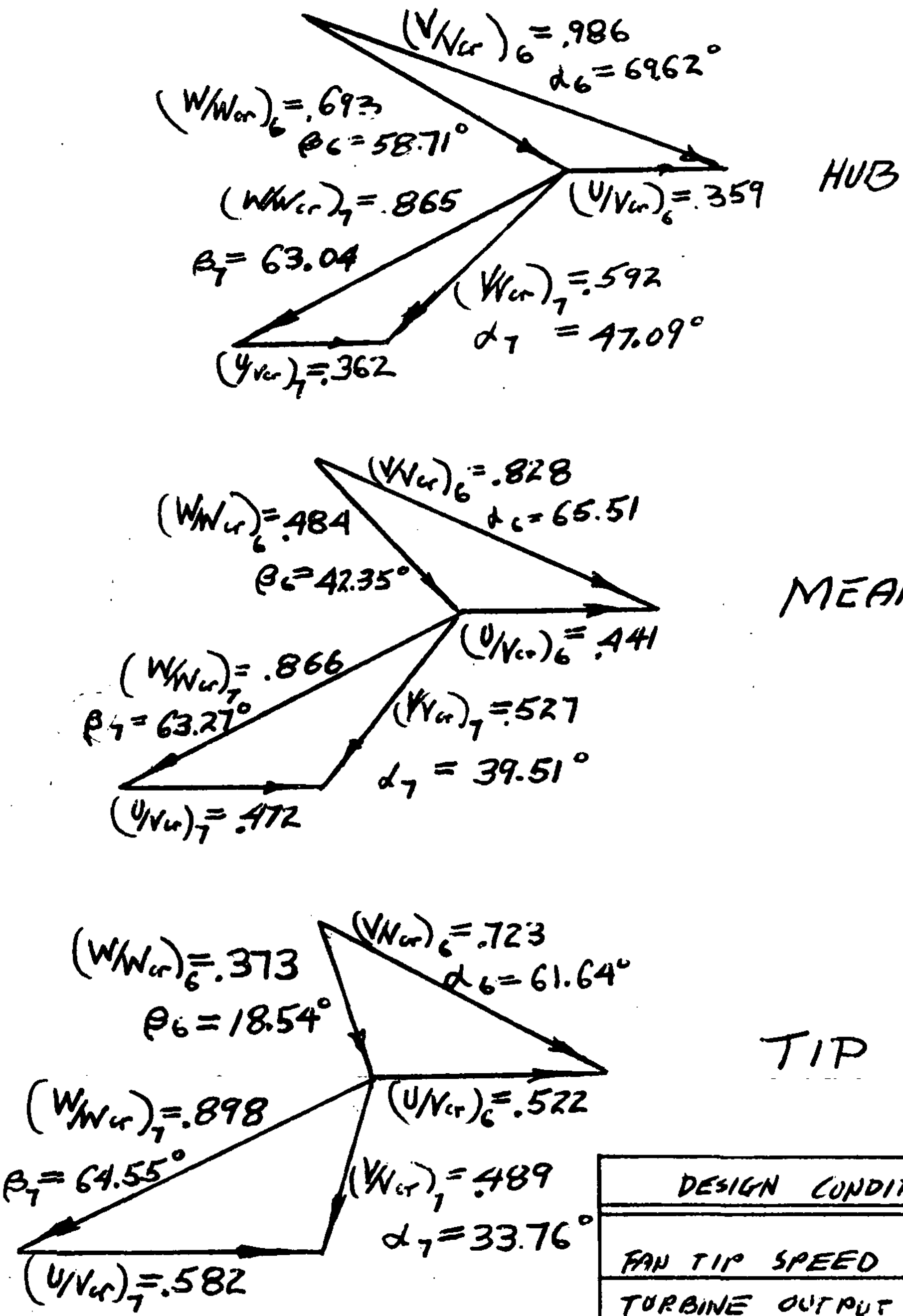


FIGURE 4 POWER-SPEED REQUIREMENTS FOR CORE TURBINE



DESIGN CONDITIONS	
FAN TIP SPEED	1035 f.p.s.
TURBINE OUTPUT	2082 HP
INLET PRESSURE, p'_5	270 psia
OUTLET PRESSURE p'_7	29.75 psia
INLET TEMPERATURE, T'_5	200°F
MASS FLOW	21.8 LB/SEC

FIGURE 5 CORE TURBINE VELOCITY DIAGRAM, 4TH STAGE

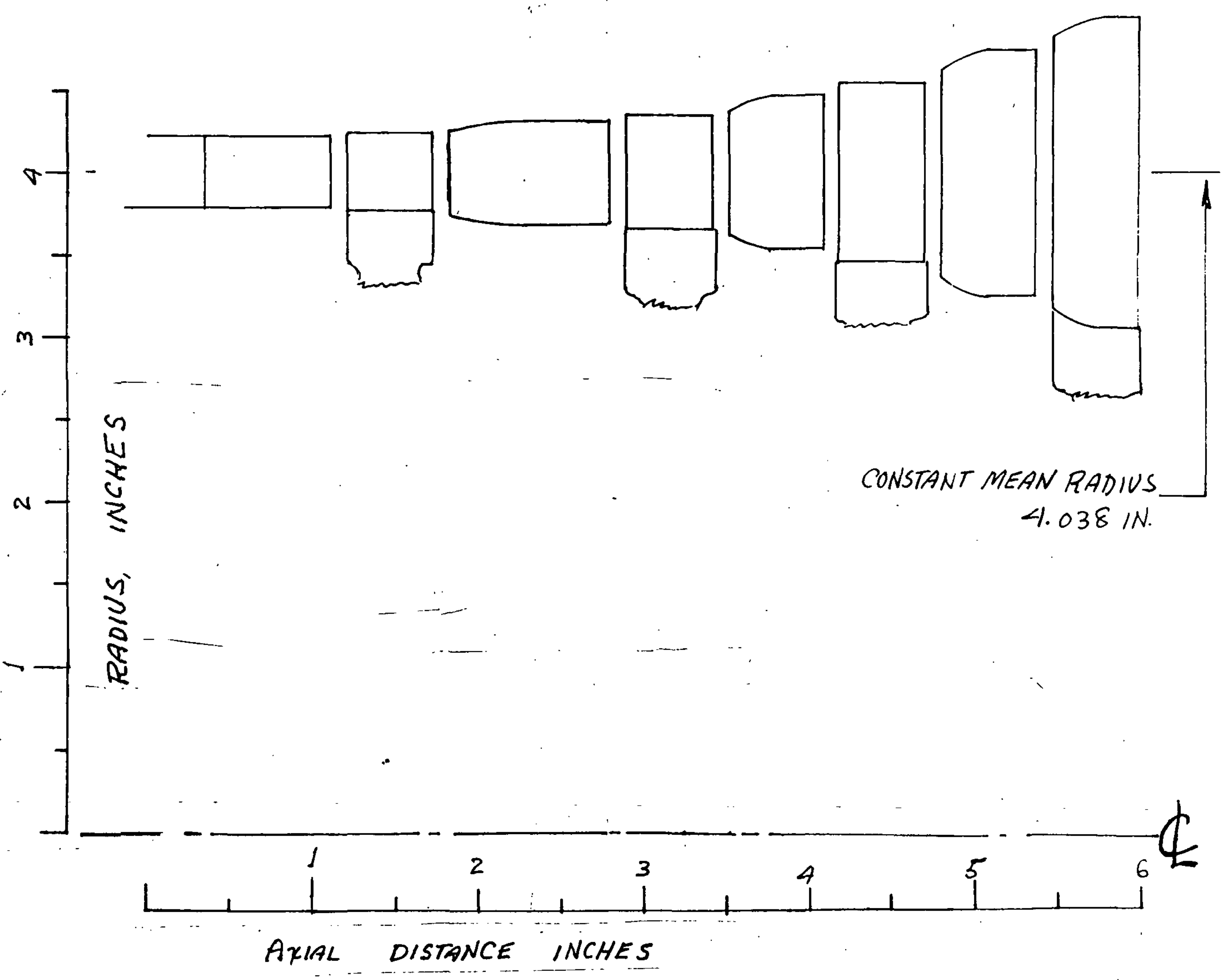


FIGURE 6. CORE TURBINE FLOW PATH

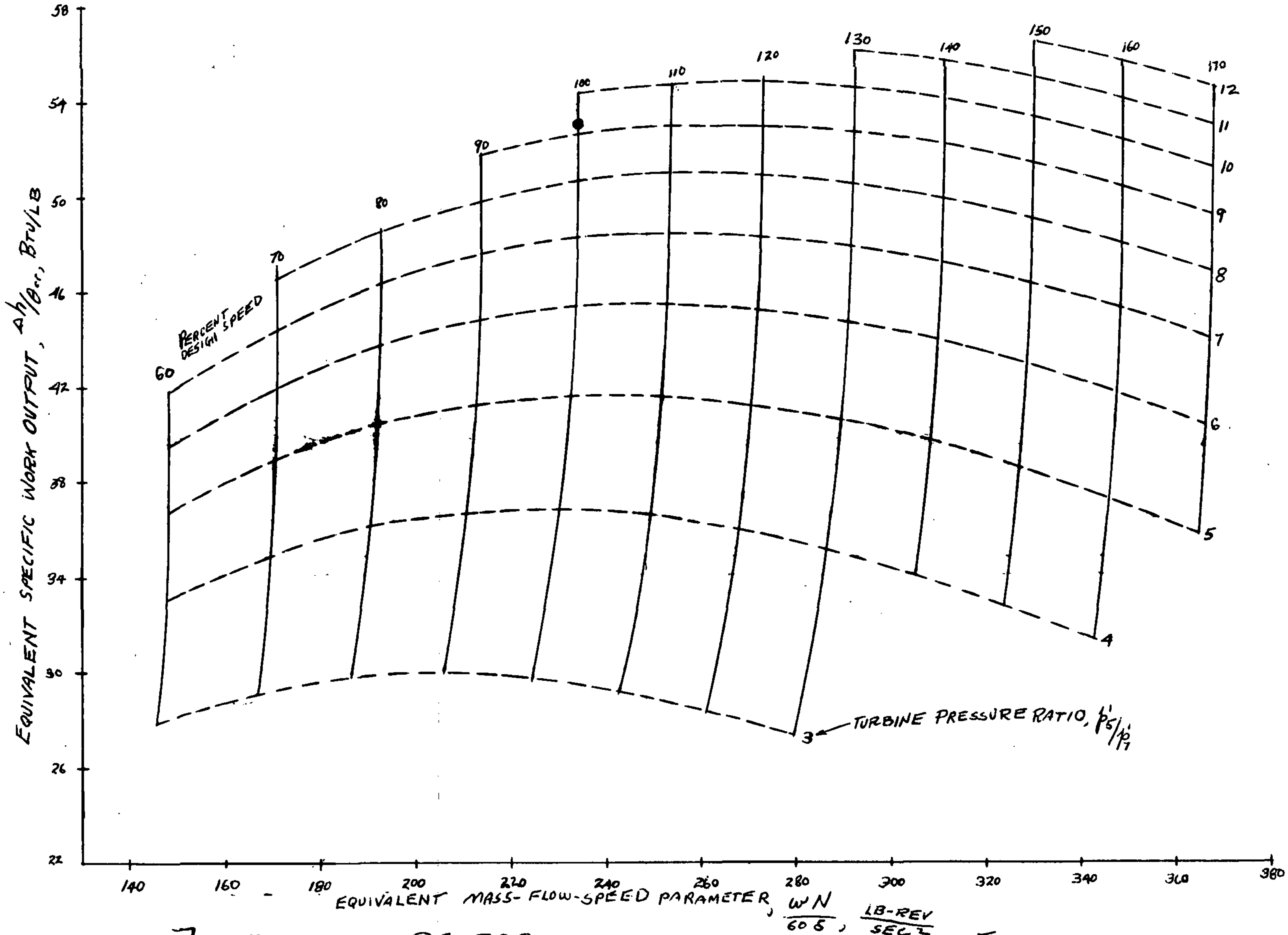


FIGURE 7 ESTIMATED PERFORMANCE MAP FOR CORE TURBINE

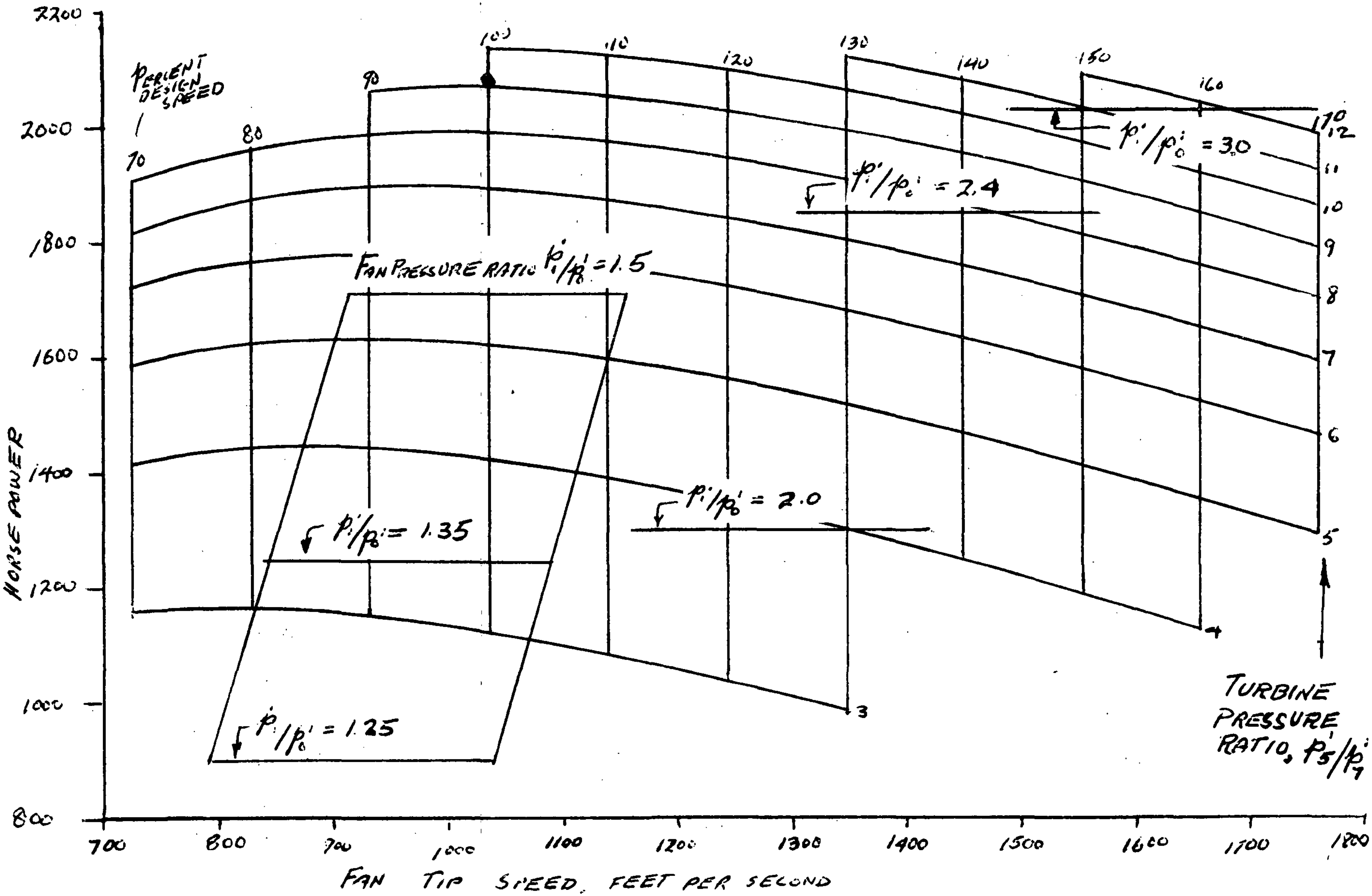


FIGURE 8 ESTIMATED POWER-SPEED ENVELOPE OF CORE TURBINE